the TI zone will be restricted to a portion of the contaminated ground-water zone, the limits of the TI zone should be delineated clearly on site maps and geologic cross-sections. Delineation of the TI zone based on the location of a particular mapped contaminant concentration contour interval (e.g., the 200 part per billion isoconcentration line) generally should be avoided. This is because the location of such mapped contours often is highly interpretive, and their position may change with time. While concentration data may be appropriate to consider when determining the size of a containment area or the extent of a TI zone, the limits of that TI zone should be fixed in space, both horizontally and vertically.

4.4.3 Development and Purpose of the Site Conceptual Model

Decisions regarding the technical practicability of ground-water restoration must be based on a thorough characterization of the physical and chemical aspects of the site. Characterization data should describe site geology and hydrology; contamination sources, properties, and distribution; release mechanisms and rates; fate and transport processes; current or potential receptors; and other elements that define the contamination problem and facilitate analysis of site restoration potential. While the elements of such a model may vary from site to site, some generalizations can be made about what such a model would contain. Examples of these elements are provided in Figure 4. The site conceptual model synthesizes data acquired from historical research, site characterization, and remediation system operation.

The site conceptual model typically is presented as a summary or specific component of a site investigation report. The model is based on, and should be supported by, interpretive graphics, reduced and analyzed data, subsurface investigation logs, and other pertinent characterization information. The site conceptual model is not a mathematical or computer model, although these may be used to assist in developing and testing the validity of a conceptual model or evaluating the restoration potential of the site. The conceptual model, like any theory or hypothesis, is a dynamic tool that should be tested and refined throughout the life of the project. As illustrated in Figure 5, the model should evolve in stages as information is gathered during the various phases of site remediation. This iterative process allows data collection efforts to be designed so that key model hypotheses may be tested and revised to reflect new information.

The conceptual model serves as the foundation for evaluating the restoration potential of the site and, thereby, technical impracticability as well. The TI determination must consider how site conditions impact the potential for achieving remediation goals and whether remediation performance, cost-effectiveness, and timeframe meet EPA requirements or expectations. As these determinations rely on professional judgment, the clarity of the conceptual model (and supporting information) is critical to the decision-making process.

4.4.4 Evaluation of Restoration Potential

4.4.4.1 Source Control Measures. Remediation of contamination sources is critical to the success of aquifer restoration efforts. Continued releases of contamination from source materials to ground water can greatly reduce the effectiveness of aquifer restoration technologies, such as pump-and-treat, which generally are effective only for removing dissolved contaminants (EPA 1989b; 1992d). EPA considers subsurface NAPLs to be source materials because they are capable of releasing significant quantities of dissolved contamination to ground water over long periods of time.

A demonstration that ground-water restoration is technically impracticable generally should be accompanied by a demonstration that contamination sources have been, or will be, identified and removed or treated to the extent practicable. EPA recognizes that locating and remediating subsurface sources can be difficult. For example, locating DNAPLs in certain complex geologic environments may be impracticable. EPA expects, however, that all reasonable efforts will be made to identify the location of source areas through historical information searches and site characterization efforts.

Source removal and remediation may be difficult, even where source locations are known. The appropriate level of effort for source removal and remediation must be evaluated on a site-specific basis, considering the degree of risk reduction and any other potential benefits that would result from such an action. Even partial removal of contamination sources can greatly reduce the long-term reliance on both active and passive ground-water remediation.

Where complete source removal or treatment is impracticable, use of migration control or containment measures should be considered. Physical and hydraulic barriers are proven technologies that are capable of limiting or preventing further contaminant

Figure 4. Elements of Site Conceptual Model

The data and analysis required for TI evaluations will be determined by EPA on a site-specific basis. This information should be presented in formats conducive to analysis and in sufficient detail to define the key site conditions and mechanisms that limit restoration potential. Types of information and analysis that may be needed for conceptual model development are illustrated below.

Background Information

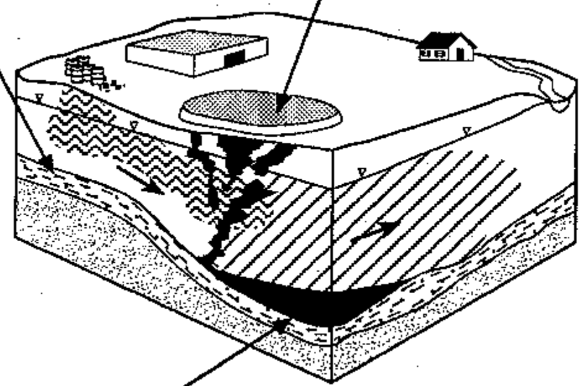
- Location of water supply wells.
- Ground-water Classification.
- Nearby wellhead protection areas or sole-source aquifers.
- Location of potential environmental receptors.

Geologic and Hydrologic Information

- Description of regional and site geology.
- Physical properties of subsurface materials (e.g., texture, porosity, bulk density).
- Stratigraphy, including thickness, lateral extent, continuity of units, and presence of depositional features, such as channel deposits, that may provide preferential pathways for, or barriers to, contaminant transport.
- Geologic structures that may form preferential pathways for NAPL migration or zones of accumulation.
- Depth to ground water.
- Hydraulic gradients (horizontal and vertical).
- Hydraulic properties of subsurface materials (e.g., hydraulic conductivity, storage coefficient, effective porosity) and their directional variability (anisotropy).
- Spatial distribution of soil or bedrock physical/hydraulic properties (degree of heterogeneity).
- Characterization of secondary porosity features (e.g., fractures, karst features) to the extent practicable.
- Temporal variability in hydrologic conditions.
- Ground-water recharge and discharge information.
- Ground-water/surface water interactions.

Contaminant Source and Release Information

- Location, nature, and history of previous contaminant releases or sources.
- Locations and characterizations of continuing releases or sources.
- Locations of subsurface sources (e.g., NAPLs).

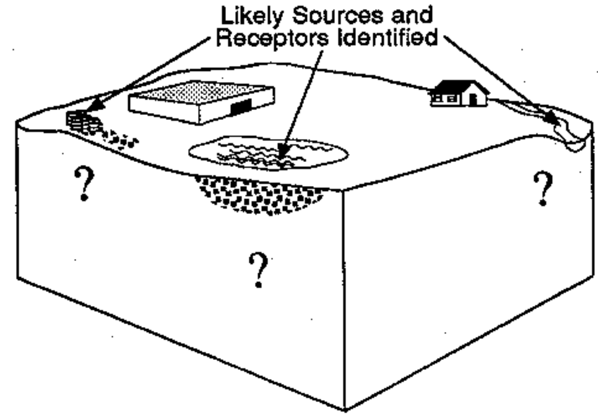


Contaminant Distribution, Transport, and Fate Parameters

- Phase distribution of each contaminant (gaseous, aqueous, sorbed, free-phase NAPL, or residual NAPL) in the unsaturated and saturated zones.
- Spatial distribution of subsurface contaminants in each phase in the unsaturated and saturated zones.
- Estimates of subsurface contaminant mass.
- Temporal trends in contaminant concentrations in each phase.
- Sorption information, including contaminant retardation factors.
- Contaminant transformation processes and rate estimates.
- Contaminant migration rates.
- Assessment of facilitated transport mechanisms (e.g., colloidal transport).
- Properties of NAPLs that affect transport (e.g., composition, effective constituent solubilities, density, viscosity).
- Geochemical characteristics of subsurface media that affect contaminant transport and fate.
- Other characteristics that affect distribution, transport, and fate (e.g., vapor transport properties).

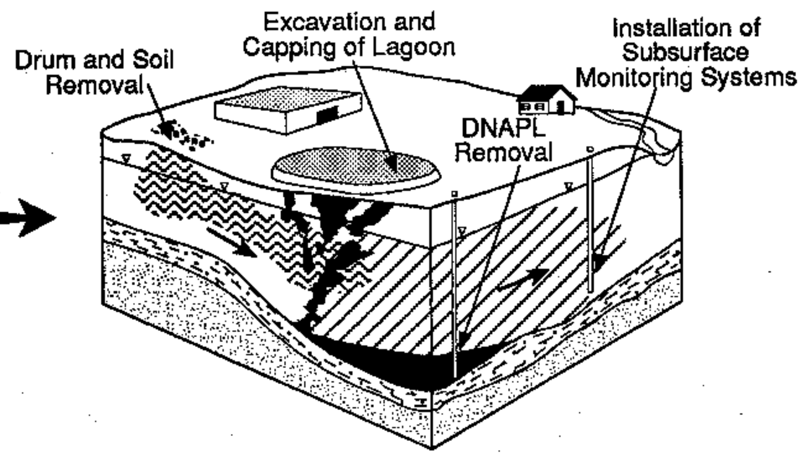
Figure 5. Evolution of the Site Conceptual Model

- Site Background and History
- Preliminary Site Investigations



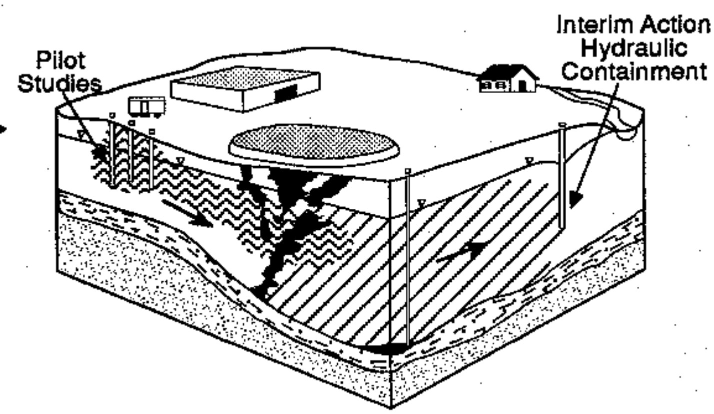
Conceptual Model Provides Basis for:

- Early Action/Removal of Near-Surface Materials
- Site Characterization Studies (RI/FS, RFI)
- Removal of Subsurface Sources (e.g., free-phase NAPLs)



Conceptual Model Provides Basis for:

- Pilot Studies
- Interim Ground-Water Actions



Conceptual Model Provides Basis for:

- Evaluation of Restoration Potential (or TI)
- Full-Scale Treatment System Design and Implementation
- Performance Monitoring and Evaluations
- Enhancement or Augmentation of Remediation System, if Required
- Future Evaluation of TI , if Required (See Figure 6)

migration from a source area under the right circumstances. While these containment measures are not capable of restoring source areas to required cleanup levels (i.e., a TI decision may be necessary for the source area), they may enable restoration of portions of the aquifer outside the containment zone.

4.4.4.2 Remedial Action Performance Analysis. The suitability and performance of any completed or ongoing ground-water remedial actions should be evaluated with respect to the objectives of those actions. Examples of remedy performance data are provided in Figure 6. The performance analysis should:

1. Demonstrate that the ground-water monitoring program within and outside of the aqueous contaminant plume is of sufficient quality and detail to fully evaluate remedial action performance (e.g., to analyze plume migration or containment and identify concentration trends within the remediation zone).[14]

2. Demonstrate that the existing remedy has been effectively operated and adequately maintained.

3. Describe and evaluate the effectiveness of any remedy modifications (whether variations in operation, physical changes, or augmentations to the system) designed to enhance its performance.

4. Evaluate trends in subsurface contaminant concentrations. Consider such factors as whether the aqueous plume has been contained, whether the areal extent of the plume is being reduced, and the rates of contaminant concentration decline and contaminant mass removal. Further considerations include whether aqueous-phase concentrations rebound when the system is shut down, whether dilution or other natural attenuation processes are responsible for observed trends, and whether contaminated soils on site are contaminating the ground water.

Analysis of aqueous-phase concentration data should be performed with caution. Contaminant concentrations plotted as a function of time, pore volumes of flushed fluids, or other appropriate variables may be useful in evaluating dominant contaminant fate and transport processes, evaluating remedial system design, and predicting future remedial system performance. Sampling methodologies, locations, and strategies, however, should be analyzed to determine the impact they may have had on observed concentration trends. For example, studies of ground-water extraction systems indicate that some systems show rapid initial decreases in aquifer concentration, followed by less dramatic decreases that eventually approach an asymptotic concentration level (EPA 1989b, 1992d). This "leveling off" effect may represent either a physical limitation to further remediation (e.g., contaminant diffusion from low permeability units) or an artifact of the system design or monitoring program. Professional judgment must be applied carefully when drawing conclusions concerning restoration potential from this information.

In certain cases, EPA may determine that lack of progress in achieving the required cleanup levels has resulted from system design inadequacies, poor system operation, or unsuitability of the technology for site conditions. Such system-related constraints are not sufficient grounds for determining that ground-water restoration is technically impracticable. In such instances, EPA generally will require that the existing remedy be enhanced, augmented, or replaced by a different technology. Furthermore, EPA may require modification or replacement of an existing remedy to ensure protectiveness, regardless of whether or not attainment of required cleanup levels is technically impracticable.

4.4.4.3 Restoration Timeframe Analysis. Estimates of the timeframe required to achieve ground-water restoration may be considered in TI evaluations. While restoration timeframes may be an important consideration in remedy selection, no single timeframe can be specified during which restoration must be achieved to be considered technically practicable. However, very long restoration timeframes (e.g., longer than 100 years) may be indicative of hydrogeologic or contaminant-related constraints to remediation. While predictions of restoration timeframes may be useful in illustrating the effects of such constraints, EPA will base TI decisions on an overall demonstration of the extent of such physical constraints at a site, not on restoration timeframe analyses alone. Such demonstrations should be based on detailed and accurate site conceptual models that also can provide the bases for meaningful predictions of restoration timeframes.

14 Further guidance on design of performance monitoring for remedial actions at ground-water sites is provided in "General Methods for Remedial Operations Performance Evaluations," EPA Office of Research and Development Publication EPA/600/R-92/002, January 1992 (EPA 1992e).

Figure 6. Remedy Performance Analysis

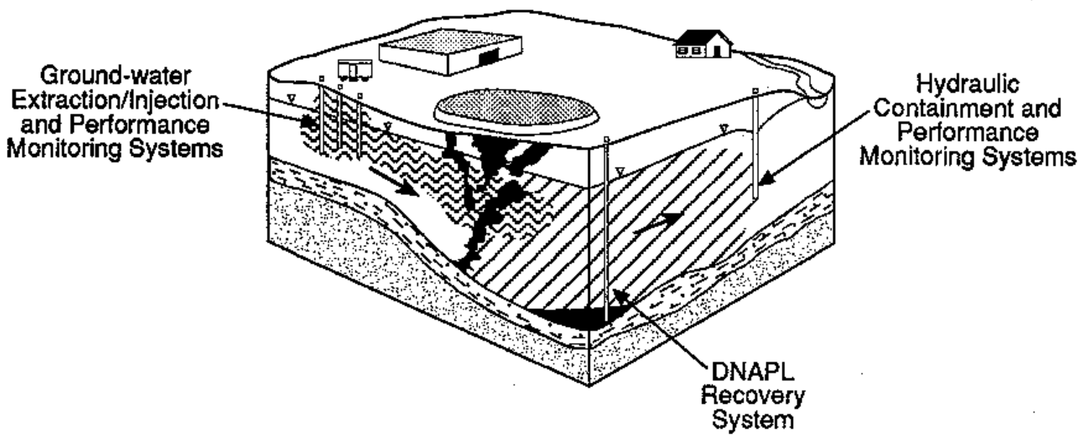
Remedy design and performance data requirements should be specific to technologies employed and site conditions. The categories of required information normally necessary to evaluate performance are provided below with some examples of specific data elements. These data should be reported to EPA in formats conducive to analysis and interpretation. Simple data compilations are insufficient for this purpose.

Remedy Design and Operational Information

- Design and as-built construction information, including locations of extraction or *in situ* treatment points with respect to the contamination.
- Supporting design calculations (e.g., calculation of well spacing).
- Operating information pertinent to remedy (e.g., records of the quantity and quality of extracted or injected fluids).
- Percent downtime and other maintenance problems.

Enhancements to Original Remedial Design

- Information concerning operational modifications, such as variations in pumping, injection rates, or locations.
- Rationale, design, and as-built construction information for system enhancements.
- Monitoring data and analyses that illustrate the effect these modifications have had on system performance.



Source Removal or Control

- Source removal information (e.g., results of soil excavations, removal of lagoon sediments, NAPL removal activities).
- Source control information (e.g., results of NAPL containment, capping of former waste management units).

Performance Monitoring Information

- Design and as-built construction information for performance monitoring systems.
- Hydraulic gradients and other information demonstrating plume containment or changes in areal extent or volume.
- Trends in subsurface contaminant concentrations determined at several/many appropriate locations in the subsurface. Trends should be displayed as a function of time, a function of pore volumes of flushed fluids, or other appropriate measures.
- Information on types and quantities of contaminant mass removed and removal rates.

A further consideration regarding the usefulness of restoration timeframe predictions in TI evaluations is the uncertainty inherent in such analyses. Restoration timeframes generally are estimated using mathematical models that simulate the behavior of subsurface hydrologic processes. Models range from those with relatively limited input data requirements that perform basic simulations of ground-water flow only, to those with extensive data requirements that are capable of simulating multi-phase flow (e.g., water, NAPL, vapor) or other processes such as contaminant adsorption to, and desorption from, aquifer materials. Model input parameters generally are a combination of values measured during site characterization studies and values assumed based on scientific literature or professional judgment. The input parameter selection process, as well as the simplifying assumptions of the mathematical model itself, result in uncertainty of the accuracy of the output. Restoration timeframes predicted using even the most sophisticated modeling tools and data, therefore, will have some degree of uncertainty associated with them.

Restoration timeframe analyses, therefore, generally are well suited for comparing two or more remediation design alternatives to determine the most appropriate strategy for a particular site. Where employed for such purposes, restoration timeframe analyses should be accompanied by a thorough discussion of all assumptions, including a list of measured or assumed parameters and a quantitative analysis, where appropriate, of the degree of uncertainty in those parameters and in the resulting timeframe predictions. The uncertainty in the predictions should be factored into the weight they are given in the remedy decision process.

4.4.4.4 Other Applicable Technologies. The TI evaluation should include a demonstration that no other remedial technologies or strategies would be capable of achieving ground-water restoration at the site.[15] The type of demonstration required will depend on the circumstances of the site and the state of ground-water remediation science at the time such an evaluation is made. In general, EPA expects that such a demonstration should consist of: 1) a review of the technical literature to identify candidate technologies; 2) a screening of the candidate technologies based on general site conditions to identify potentially applicable technologies; and 3) an analysis, using site hydrogeologic and chemical data, of the capability of any of the applicable technologies to achieve the required cleanup standards. Analysis of the potentially applicable technologies generally can be performed as a "paper study." EPA, however, may reserve the right to require treatability or pilot testing demonstrations to determine the actual effectiveness of a technology at a particular site.

Treatability and pilot testing should be conducted with rigorous controls and mass balance constraints. Information required by EPA for evaluation of pilot tests will be similar to that required for evaluation of existing remediation systems (e.g., detailed design and performance data).

4.4.4.5 Additional Considerations. Techniques used for evaluation of ground-water restoration potential are still evolving. The results of such evaluations generally will have some level of uncertainty associated with them. Interpretation of the results of restoration potential evaluations, therefore, will require the use of professional judgment. The use of mathematical models and calculations of mass removal rates are two examples of techniques that require particular caution.

Ground-water Flow and Contaminant Transport/Fate Modeling. Simulation of subsurface systems through mathematical modeling can be useful for designing remediation systems or predicting design performance. However, the limitations of predictive modeling must be considered when evaluating site restoration potential. As discussed in Section 4.4.4.3, ground-water models are sensitive to initial assumptions and the choice of parameters, such as contaminant source locations, leachability, and hydraulic conductivity. Predictions such as the magnitude and distribution of subsurface contaminant concentrations, therefore, will involve uncertainty. The source and degree of this uncertainty should be described, quantified, and evaluated wherever possible so the reviewer understands the level of confidence that should be placed in the predicted concentration values or other outputs. Predictive modeling may be most valuable in providing insight into processes that dominate contaminant transport and fate at the site and evaluating the relative effectiveness of different remedial alternatives. Further guidance and information on the use of ground-water models is provided in Anderson and Woessner (1992), EPA (1992f), and EPA (1992g).

Contaminant Mass Removal Estimates. Evaluation of contaminant mass removal may be useful at some sites

15 See discussions in the NCP (55 FR 8748, March 8, 1990) and Subpart S (55 FR 30838, July 27, 1990).

with existing remediation systems. These measures may include evaluation of mass removal rates, comparison of removal rates to *in situ* mass estimates, changes in the size of the contaminated area, comparison of mass removal rates with pumping rates, and comparison of such measures with associated costs. Mass removal and balance estimates should be used with caution, as there often is a high degree of uncertainty associated with estimates of the initial mass released and the mass remaining *in situ*. This uncertainty results from inaccuracy of historical site waste-management records, subsurface heterogeneities, and the difficulty in delineating the severity and extent of subsurface contamination.

4.4.5 Cost Estimate

Estimates of the cost of remedy alternatives should be provided in the TI evaluation. The estimates should include the present worth of construction, operation, and maintenance costs. Estimates should be provided for the continued operation of the existing remedy (if the evaluation is conducted following implementation of the remedy) or for any proposed alternative remedial strategies.

As discussed in Section 4.4.1, a Superfund remedy alternative may be determined to be technically impracticable if the cost of attaining ARARs would be inordinately high. The role of cost, however, is subordinate to that of ensuring protectiveness. The point at which the cost of ARAR compliance becomes inordinate must be determined based on the particular circumstances of the site. As with long restoration timeframes, relatively high restoration costs may be appropriate in certain cases, depending on the nature of the contamination problem and considerations such as the current and likely future use of the ground water. Compliance with ARARs is not subject to a cost-benefit analysis, however.[16]

5.0 Alternative Remedial Strategies

5.1 Options and Objectives for Alternative Strategies[17]

EPA's goal of restoring contaminated ground water within a reasonable timeframe at Superfund or RCRA sites will be modified where complete restoration is found to be technically impracticable. In such cases, EPA will select an alternative remedial strategy that is technically practicable, protective of human health and the environment, and satisfies the statutory and regulatory requirements of the Superfund or RCRA programs, as appropriate.[18]

Where a TI decision is made at the "front end" of the site remediation process (before a final remedy has been identified and implemented), the alternative strategy should be incorporated into a final remedy decision document, such as a Superfund ROD or RCRA permit or enforcement order. Where the TI decision is made after the final decision document has been signed (i.e., after a remedy has been implemented and its performance evaluated), the alternative remedial strategy should be incorporated in a modified final remedy decision document, such as a ROD amendment or RCRA permit/order modification (see Section 6.0).

Alternative remedial strategies typically will address three types of problems at contaminated ground-water sites: prevention of exposure to contaminated ground water; remediation of contamination sources; and remediation of aqueous contaminant plumes. Recommended objectives and options for addressing these three problems are discussed below. Note that combinations of two or more options may be appropriate at any given site, depending on the size and complexity of the contamination problem or other site circumstances.

5.1.1 Exposure Control

Since the primary objective of any remedial strategy is overall protectiveness, exposure prevention may play a significant role in an alternative remedial strategy. Exposure control may be provided using institutional controls, such as deed notifications and restrictions on water-supply well construction and use. The remedy should provide assurance that these measures are enforceable and consistent with State or local laws and ordinances.

5.1.2 Source Control

Source remediation and control should be considered when developing an alternative remedial strategy.

16 A Fund-Balancing ARAR waiver may be invoked at Fund-lead Superfund sites where meeting an ARAR would entail such cost in relation to the added degree of protection or reduction of risk that remedial actions at other sites would be jeopardized (EPA 1989c).

17 These recommendations are consistent with those made in Section 3.0 concerning DNAPL sites, but are applicable for any site where restoration is technically impracticable.

18 PRPs or owner/operators may propose and analyze alternative remedial strategies. However, only EPA (or designated lead agency, where appropriate) has remedy selection authority.

Sources should be located and treated or removed where feasible and where significant risk reduction will result, regardless of whether EPA has determined that ground-water restoration is technically impracticable.

In some cases, however, the inability to remove or treat sources will be a major factor in a TI decision. Where sources cannot be completely treated or removed, effective source containment may be critical to the long-term effectiveness and reliability of an alternative ground-water remedy. Options currently available for source containment usually involve either a physical barrier system (such as a slurry wall) or a hydraulic containment system (typically a pump-and-treat system) (EPA 1992b).

Applicability and effectiveness of containment systems are influenced by several hydrogeologic factors, however. For example, the effectiveness of a slurry wall generally depends on whether a continuous, low permeability layer exists at a relatively shallow depth beneath the site.

Source containment has several benefits. First, source containment will contribute to the long-term management of contaminant migration by limiting the further contamination of ground water and spread of potentially mobile sources, such as NAPLs. Second, effective source containment may permit restoration of that portion of the aqueous plume that lies outside of the containment area. Third, effective containment may facilitate the future use of new source removal technologies, as some of these technologies (e.g., surfactants, steam injection, radio frequency heating) may increase the mobility of residual and free-phase NAPLs. Remobilization of NAPLs, particularly DNAPLs, often presents a significant risk unless the source area can be reliably contained.

5.1.3 Aqueous Plume Remediation

Remediation of the aqueous plume is the third major technical concern of an alternative remedial strategy. Where the technical constraints to restoration include the inability to remove contamination sources, the ability to effectively contain those sources will be critical to establishing the objectives of plume remediation. Where sources can be effectively contained, the portion of the aqueous plume outside of the containment area generally should be restored to the required cleanup levels.

Inability to contain the sources, or other technical constraints, may render plume restoration technically impracticable. There are several options for alternative remedial strategies in such cases. These include hydraulic containment of the leading edge of the aqueous plume, establishing a less-stringent cleanup level that would be actively sought throughout the plume (at Superfund sites), and natural attenuation or natural gradient flushing of the plume.

Containment of the aqueous plume usually requires the pumping and treating of contaminated ground water, but usually involves fewer wells and smaller quantities of water than does a full plume restoration effort. Plume containment offers the potential advantages of preventing further spreading of the contaminated ground water, thereby limiting the size of the plume, and preventing the plume from encroaching on water-supply wells or discharging to ecologically sensitive areas.

At certain Superfund sites, it may be feasible to restore the contaminated plume (outside of any source containment area) to a site-specific cleanup level that is less stringent than that originally identified. EPA may establish such a level as the cleanup level within the TI zone, where appropriate. The site-specific level may consider the targeted risk level for site cleanup and other factors. Site-specific cleanup levels offer the advantage of providing a clear goal against which to measure the progress of the alternative remedial strategy. However, where site-specific cleanup levels exceed the acceptable risk range for human or environmental exposure, the remedy generally must include other measures (e.g., institutional controls) to ensure protectiveness.

At some Superfund sites, a less-stringent ARAR than the one determined to be unattainable may have to be complied with. For example, it may be technically impracticable to attain the most stringent ARAR at a site (e.g., a State requirement to restore ground water to background concentration levels). However, the next most stringent ARAR (e.g., Federal MCL) for the same compound may be attainable. In such cases, the next most stringent ARAR generally must be attained.

In certain situations where restoration is technically impracticable, EPA may choose natural attenuation as a component of the remedy for the aqueous plume.[19] Natural attenuation generally will result in

19 Technical impracticability of restoration is not a precondition for the use of natural attenuation in a ground-water remedy, however.